AFRL-RY-WP-TP-2010-1243

5-W YELLOW LASER BY INTRACAVITY FREQUENCY DOUBLING OF HIGH-POWER VERTICAL-EXTERNAL-CAVITY SURFACE-EMITTING LASER (POSTPRINT)

Mahmoud Fallahi, Li Fan, Chris Hessenius, Jörg Hader, Hongbo Li, and Jerome V. Moloney

University of Arizona

Bernardette Kunert, Wolfgang Stolz, and Stephan W. Koch

Philipps Universität Marburg

James T. Murray

Areté Associates

Robert Bedford

Electro Optic Components Branch
Aerospace Components and Subsystems Technology Division

OCTOBER 2008

AIR FORCE RESEARCH LABORATORY
SENSORS DIRECTORATE
WRIGHT-PATTERSON AIR FORCE BASE, OH 45433-7320
AIR FORCE MATERIEL COMMAND
UNITED STATES AIR FORCE

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YY)*	2. REPORT TYPE	3. DATES COVERED *(From - To)*
October 2008	Journal Article Postprint	01 January 2008 – 01 September 2008

4. TITLE AND SUBTITLE
5-W YELLOW LASER BY INTRACAVITY FREQUENCY DOUBLING OF HIGH-POWER VERTICAL-EXTERNAL-CAVITY SURFACE-EMITTING LASER (POSTPRINT)

5a. CONTRACT NUMBER
In-house

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER
62204F

6. AUTHOR(S)
Mahmoud Fallahi, Li Fan, Chris Hessenius, Jörg Hader, Hongbo Li, and Jerome V. Moloney (University of Arizona)
Bernardette Kunert, Wolfgang Stolz, and Stephan W. Koch (Philipps Universität Marburg)
James T. Murray (Areté Associates)
Robert Bedford (AFRL/RYDP)

5d. PROJECT NUMBER
2002

5e. TASK NUMBER
IH

5f. WORK UNIT NUMBER
2002IH0E

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

University of Arizona
Arizona Center for Mathematical Sciences
Tucson, AZ 85721

Philipps Universität Marburg
Department of Physics and Material Sciences Center
Renthof 5, 35032
Marburg, Germany

Areté Associates
1225 Ken Pratt Boulevard
Longmont, CO 80501

Electro Optic Components Branch (AFRL/RYDP)
Aerospace Components and Subsystems Technology Division
Air Force Research Laboratory
Sensors Directorate
Wright-Patterson Air Force Base, OH 45433-7320
Air Force Materiel Command
United States Air Force

8. PERFORMING ORGANIZATION REPORT NUMBER
AFRL-RY-WP-TP-2010-1243

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Air Force Research Laboratory
Sensors Directorate
Wright-Patterson Air Force Base, OH 45433-7320
Air Force Materiel Command
United States Air Force

10. SPONSORING/MONITORING AGENCY ACRONYM(S)
AFRL/RYDP

11. SPONSORING/MONITORING AGENCY REPORT NUMBER(S)
AFRL-RY-WP-TP-2010-1243

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited.

13. SUPPLEMENTARY NOTES
Journal article published in *IEEE Photonics Technology Letters*, Vol. 20, No. 20, October 15, 2008. PAO Case Number: 88ABW-08-3883; Clearance Date: 26 Jun 2008. Paper contains color.

14. ABSTRACT
We report on the development of a high-power tunable yellow–orange laser. It is based on intracavity frequency doubling of a widely tunable, highly strained InGaAs–GaAs vertical-external-cavity surface-emitting laser operating near 1175 nm. Over 5 W of continuous-wave output power is achieved and is tunable over a 15-nm band centered at 587 nm. This compact low-cost high-power yellow–orange laser provides an innovative alternative for sodium.

15. SUBJECT TERMS
lasers, semiconductor

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT:	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON (Monitor)
Unclassified	Unclassified	Unclassified	SAR	10	Robert Bedford
					19b. TELEPHONE NUMBER *(Include Area Code)* N/A

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. Z39-18

5-W Yellow Laser by Intracavity Frequency Doubling of High-Power Vertical-External-Cavity Surface-Emitting Laser

Mahmoud Fallahi, Li Fan, Yushi Kaneda, Chris Hessenius, Jörg Hader, Hongbo Li, Jerome V. Moloney, Bernardette Kunert, Wolfgang Stolz, Stephan W. Koch, James Murray, and Robert Bedford

***Abstract*—We report on the development of a high-power tunable yellow–orange laser. It is based on intracavity frequency doubling of a widely tunable, highly strained InGaAs–GaAs vertical-external-cavity surface-emitting laser operating near 1175 nm. Over 5 W of continuous-wave output power is achieved and is tunable over a 15-nm band centered at 587 nm. This compact low-cost high-power yellow–orange laser provides an innovative alternative for sodium guidestar lasers, medical and communication applications.**

***Index Terms*—Intracavity frequency doubling, optically pumped semiconductor lasers, tunable vertical-external-cavity surface-emitting laser (VECSEL).**

I. Introduction

HIGH-POWER laser sources covering the 570- to 590-nm bands are of great interest for a wide range of applications including sodium guidestar laser, quantum computing, and medical applications [1], [2]. Despite the wide range of applications, the development of yellow–orange lasers has been limited, primarily due to a lack of gain materials within this band. Nonlinear frequency conversion has frequently been used to generate emission in the yellow–orange range. Several methods including frequency doubling of Yb solid-state lasers [3], frequency doubling of Raman-shifted Yb (Nd) lasers [4], and frequency doubling of Bi-doped fiber lasers [5] have been investigated. Unfortunately a majority of these approaches suffer from limited emission range, low output power, and high cost. Development of a semiconductor-based yellow laser is very attractive for their high-gain, large volume production, and low cost. Strained multiquantum-well semiconductor lasers are widely used in the near infrared range. However, due to their limited direct bandgap energy, a range of visible emission wavelengths are difficult to fabricate.

Optically pumped vertical-external-cavity surface-emitting lasers (VECSELs) using multiquantum wells are very attractive as low-cost high-power high-brightness sources [6], [7]. In addition, by having access to the intracavity, several attractive features such as wavelength tuning, frequency doubling for visible generation, and Q-switching can be achieved.

Here we report on the development and demonstration of a highly strained InGaAs–GaAs VECSEL which can cover a significantly longer wavelength range of 1147–1197 nm. Very robust multi-Watt high-brightness performance at room temperature is demonstrated. Using intracavity frequency doubling we demonstrate high-power coherent emission in a wide yellow–orange band (575–595 nm).

II. Design and Fabrication

Strained InGaAs–GaAs quantum-well (QW) lasers are widely used for the generation of 900- to 1100-nm lasers. However longer wavelengths are a major challenge and require careful design and growth of the structure. The design of the 1180-nm VECSEL structure is accomplished using rigorous many-body microscopic quantum design tools and 3-D optical/thermal modeling of the device [7]. This microscopic quantum design approach utilizes a closed-loop semiconductor laser design tool that is free of adjustable fit parameters, and rigorously computes the low-intensity photoluminescence (PL) spectra, semiconductor gain (and refractive index) spectra, and spontaneous and Auger recombination losses for the specific QW structure. Computed low-intensity PL spectra are used for wafer diagnostics and quality control. The quantum design is then coupled with 3-D optical/thermal modeling of the device. A highly strain compensated InGaAs–GaAs–GaAsP multiquantum well in a resonant periodic gain (RPG) structure was designed using the modeling tool.

The designed InGaAs–GaAs VECSEL structure was grown using a low-temperature metal–organic vapor phase epitaxial (MOVPE) process. MOVPE growth uses alternative group-V liquid sources [tertiarybutylarsine (TBA); tertiarybutylphosphine (TBP)] that decompose at lower temperatures than the conventional hydride precursors [8]. This allows for a general

Manuscript received June 17, 2008; revised July 19, 2008. First published August 22, 2008; current version published September 26, 2008. This work was supported by the U.S. Air Force Office of Scientific Research under a Phase II STTR Grant (FA9550-06-C-0044). The work of M. Fallahi was supported by the National Science Foundation (NSF).

M. Fallahi, Y. Kaneda, C. Hessenius, and H. Li are with the College of Optical Sciences, University of Arizona, Tucson, AZ 85721 USA (e-mail: fallahi@optics.arizona.edu).

L. Fan was with the College of Optical Sciences, University of Arizona, Tucson, AZ 85721 USA, and is now with LaserTel Inc., Tucson, AZ 85743 USA.

J. Hader and J. V. Moloney are with the Nonlinear Control Strategies, Tucson, AZ 85705 USA, and also with the Arizona Center for Mathematical Sciences, University of Arizona, Tucson, AZ 85721 USA.

B. Kunert, W. Stolz, and S. W. Koch are with the Department of Physics and Material Sciences, Philipps Universität Marburg, 35032 Marburg, Germany.

J. Murray is with Areté Associates, Longmont, CO 80501 USA.

R. Bedford is with the Air Force Research Laboratory, Wright-Patterson Air Force Base, OH 45433 USA.

Color versions of one or more of the figures in this letter are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/LPT.2008.2003413

reduction of the growth temperature, promoting higher values of strain and, thus, reproducibly higher indium-concentrations in the active QW. In addition, GaAsP barriers with precise chemical composition are grown to balance the QW strain. These factors enable growth of InGaAs epitaxial structure achieving lasing at the target wavelength of 1175 nm.

The VECSEL structure consists of ten repeats of compressive strained InGaAs QWs. Each QW is 7 nm thick and surrounded by GaAsP strain compensation layers and GaAs barriers, in which the 808-nm pump emission is absorbed. The thickness and compositions of the layers are optimized such that each QW is positioned at the antinodes of the cavity standing wave to provide RPG in the active region. A high reflectivity $(R > 99.5\%)$ distributed Bragg reflector (DBR) stack made of 21 pairs of AlGaAs–AlAs is grown on the top of the active region. To avoid premature thermal rollover, a detuning between QW gain peak and microcavity resonance of about 30 nm is introduced which compensates the thermal detuning at higher temperatures and powers at the expense of a slight increase in threshold power.

Extraction of the quantum defect heat from the active region presents another challenge in the development of high-power lasers. The large energy difference between the pump and lasing wavelength lowers the quantum efficiency of the laser and generates more waste heat in the active region. For efficient heat dissipation, after a thin Ti–Au metallization, the epitaxial side of the wafer is mounted on a chemical vapor deposition diamond heat spreader using indium solder. The GaAs substrate is then completely removed by selective wet chemical etching. The remaining semiconductor, consisting of a DBR stack and RPG active layers, is about 6 μm thick allowing efficient heat extraction at high pumping energy. The surface quality of the VECSEL sample is characterized by a WYKO NT-2000 interferometer, and a peak-to-valley height of less than 40 nm over an area of 0.5 mm $\times$ 0.5 mm is measured. This optically smooth surface makes the scattering/diffraction loss negligible and results in high slope efficiency and high beam quality. Finally in order to reduce the surface reflectivity and subcavity resonance effect a dielectric antireflection (AR) coating is deposited. The processed VECSEL chip is mounted on a heat sink for temperature control.

III. Experimental Results

To generate a coherent fundamental and yellow–orange laser, we used the folded cavity of Fig. 1, in which the VECSEL chip and a flat mirror serve as two end mirrors and a concave spherical mirror as the folding mirror. L1 and L2 are around 10 and 4.5 cm, respectively, with a full folding angle of about 30°. The folding concave mirror with a radius of curvature of 75 mm is high-reflective coated for the fundamental laser but is highly transmissive (∼95%) at the yellow–orange wavelength. The laser is characterized by focusing an incoherent fiber-coupled 808-nm pump source on the chip with a spot size of 500 μm in diameter. First in order to characterize the performance of the fundamental (∼1175 nm) VECSEL, a flat output mirror with a reflectivity of 96% is used. Fig. 2 shows the performance of the laser at 15 °C and 25 °C heat-sink temperatures for a 500-μm

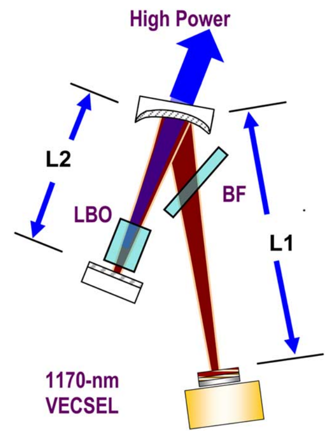

Fig. 1. Schematic of the VECSEL cavity setup for yellow–orange generation.

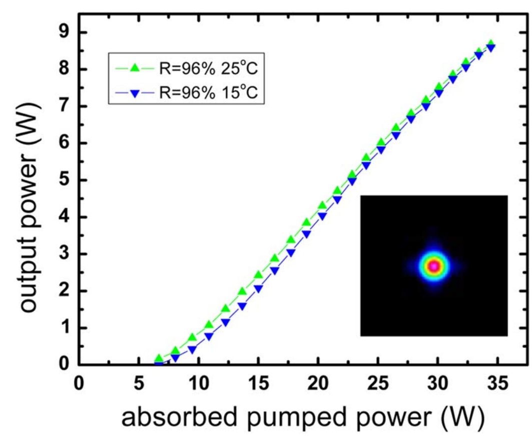

Fig. 2. VECSEL fundamental output power versus net pump power and the beam quality at 7-W output $(M^2 < 1.5)$.

pump spot. Maximum continuous-wave output power can reach 8.6 W at room temperature. The slope efficiency is around 35% at room temperature. The M^2 factor slowly increases from 1.03 at threshold to 1.5- at 8.6-W output, indicating a near TEM_{00} transverse mode at high-power operation. At an output power of 8 W, the free lasing wavelengths are 1174 and 1175 nm at 15 °C and 25 °C, respectively. Linewidth narrowing and wavelength tuning is achieved by using an intracavity birefringent filter (BF), which is inserted at Brewster's angle. By using this low-loss filter, we can achieve over 30-nm wavelength tuning. The output power variation is less than 10% in the tuning range of 1170–1180 nm, making the laser suitable for yellow–orange operation.

For efficient intracavity frequency doubling, we increased the cavity Q by replacing the 96% flat outcoupler with a highly reflecting mirror. In such a cavity the fundamental wavelength can be further tuned in the1150- to 1195-nm wavelength range. A lithium triborate (LBO) crystal with a size of 3 mm $\times$ 3 mm $\times$ 10 mm normally cut for the 1178- to 589-nm conversion is then inserted close to the flat mirror, providing a Type-I angular phase-matching condition (Fig. 1). Both facets of the LBO are AR coated for both the fundamental laser (1178 nm) and SHG signal (589 nm). Fig. 3 shows the total yellow output for a 500-μm pump spot size. At this pump spot, over 5 W at 585

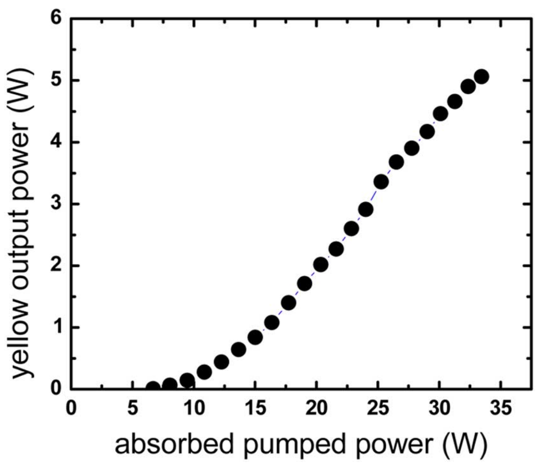

Fig. 3. Yellow laser output power versus the absorbed pump power.

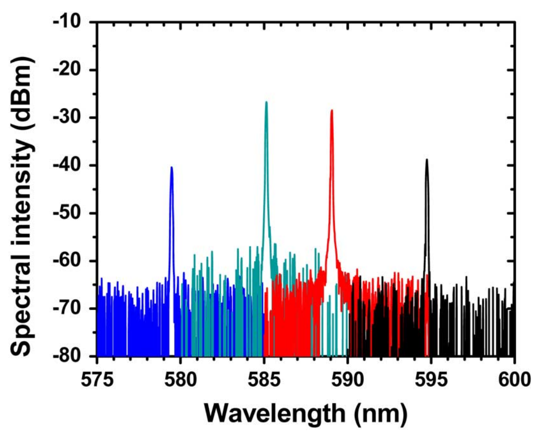

Fig. 4. Yellow–orange wavelength tuning spectra.

and 589 nm is generated. The overall pump optical power to yellow optical conversion efficiency exceeds 14% at 589-nm SHG, which is the result of high-performance fundamental generation and the efficiency of intracavity frequency doubling. A wide tuning range covering 580 to 595 nm is also achieved (Fig. 4). In the tuning range, we lock the fundamental wavelength at 1159, 1170, 1178, and 1190 nm, respectively, and align the phase matching angle of the LBO crystal to optimize the yellow–orange output. The yellow laser linewidth is around four angstroms, and can be further reduced to subangstrom by incorporating an intracavity Fabry–Pérot etalon in conjunction with the BF.

IV. Conclusion

We have demonstrated an efficient yellow laser by intracavity frequency doubling of a highly strained InGaAs–GaAs tunable VECSEL laser with an output power in excess of 8 W at around 1175 nm. Full wavelength tuning in the 1150- to 1190-nm range has been demonstrated using a folded high-Q cavity. High-power broadband output in the yellow–orange band (579- to 595-nm bands) is achieved through intracavity frequency doubling. Over 5-W yellow–orange tunable output power has been demonstrated over the 585- to 589-nm bands. This laser promises to be a reliable alternative for high-power, compact, and low-cost yellow lasers.

References

[1] N. S. Sadick and R. Weiss, "The utilization of a new yellow light laser (578 nm) for the treatment of class I red telangiestasia of the lower extremites," *J. Dermatol. Surg.*, vol. 28, pp. 21–23, 2002.

[2] C. E. Max, S. S. Oliver, H. W. Friedman, J. An, K. Avicola, B. W. Beeman, H. D. Bissinger, J. M. Brase, G. V. Erbert, D. T. Gavel, K. Kanz, M. C. Liu, B. Macintosh, K. P. Neeb, J. Patience, and K. E. Waltjen, "Image improvement from a sodium-layer laser guide star adaptive optics system," *Science*, vol. 277, pp. 1649–1651, 1997.

[3] P. A. Burns, J. M. Dawes, P. Dekker, J. A. Piper, J. Li, and J. Wang, "Coupled-cavity, single-frequency, tunable CW Yb:YAB yellow microchip laser," *Opt. Commun.*, vol. 207, pp. 315–320, 2002.

[4] D. Georgiew, V. P. Gapontsev, A. G. Dronov, M. Y. Vyatkin, A. B. Rulkov, S. V. Popov, and J. R. Taylor, "Watts-level frequency doubling of a narrow line linearly polarized Raman fiber laser to 589 nm," *Opt. Express*, vol. 13, pp. 6772–6776, 2005.

[5] E. Dianov, A. Shubin, M. Melkumov, O. Medvedkov, and I. Bufetov, "High-power CW bismuth-fiber lasers," *J. Opt. Soc. Amer. B*, vol. 24, pp. 1749–1755, 2007.

[6] L. Fan, M. Fallahi, J. T. Murray, R. Bedford, Y. Kaneda, A. R. Zakharian, J. Hader, J. V. Moloney, W. Stolz, and S. W. Koch, "Tunable high-power high-brightness linearly polarized vertical-external-cavity surface-emitting lasers," *Appl. Phys. Lett.*, vol. 88, p. 021105, 2006.

[7] J. Hader, J. V. Moloney, M. Fallahi, L. Fan, and S. W. Koch, "Closed-loop design of a semiconductor laser," *Opt. Lett.*, vol. 31, pp. 3300–3302, 2006.

[8] G. B. Stringfellow, *Organometallic Vapor-Phase Epitaxy: Theory and Practice*, 2nd ed. San Diego, CA: Academic, 1999.